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Finite Element Modelling for Structural Performance of Slim Floors in Fire and Influence of Protection Materials

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Abstract: Slim floor systems are very common nowadays and various types are currently being used for the construction of high-rise buildings and car parks. Concrete in slim floor beams encases the steel beam section which helps to improve their fire resistance. Despite their higher fire resistance, several fire protection materials like intumescent coatings are often used to achieve a higher fire resistance where desired. The thermal properties and behaviour of various intumescent coating materials were previously studied through experimental investigations. This paper presents finite element analyses to simulate the response of unprotected and protected slim floor beams in fire using different simulation tools. For this purpose, fire tests conducted on unprotected slim floor beams and intumescent coating materials are modelled using research and commercial software. Results from the analyses are compared and verified with the available test data. These validated models are later combined to study the behaviour of protected slim floor beams in fire. Results from the study show that the research and the commercial software replicate the behaviour of slim floor beams and protection materials with good accuracy. Due to the presence of the intumescent coating, the protected slim floor beams displayed a better fire resistance as the temperature of the steel part remained below 400 °C even after 60-min of standard heating. The protected slim floor beams continued to support the external loads even after 120 min of heating.

Keywords: fire resistance; slim floor; intumescent coating; finite element modelling; fire protection materials

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1. Introduction

The design of steel-concrete composite floors has changed over the years and various types have now been introduced with shallower depths, the slim floor systems. Slim floor beams are amongst the trending methods of construction especially suitable for high rise buildings and car parks [1]. The preference of these beams over other composite beam types is due to their reduced depth. Their compact depth reduces the floor and the structure height.

The steel sections in slim floors being embedded within the concrete slab are protected from direct exposure to fire as only the lower flange is exposed. As a result, the fire resistance of these beams is higher in comparison to other steel-concrete composite beams [2,3]. In addition to their higher fire resistance, these floors offer numerous other advantages including, reduction in usage of construction material, lesser construction cost requirements, the possibility of accommodating services within the floor depth and reduced carbon emissions during the manufacturing process [4].

Several experimental investigations were conducted on slim floor systems to analyse their thermal and thermo-mechanical behaviour in different fire conditions. Some of these investigations were performed at the Warrington Fire Research Centre (WFRC) in collaboration with British Steel [5]. Several other tests on slim floor systems have been conducted in different parts of the work. TNO Building and Construction Research, Centre of fire research, Netherlands, conducted tests during 1995 to investigate the effect of air-fap between the welded plate and the bottom flange of the steel beam section and to assess the membrane action [6,7]. These tests were conducted on unprotected slim floor beams. Another fire test on a slim floor beam was conducted at the Polythetic University of Valencia (UPV), Spain on unloaded and unprotected specimens using an electric furnace [8]. Tests on asymmetric slim floor beams were conducted between 2010 and 2012 in the Republic of Korea when 7 asymmetric slim floor assemblies under different loads and variable section properties [9,10]. Recently during 2029–2021, detailed experimental investigations on slim floor beams have been conducted at Ulster University where the effect of steel reinforcement as an alternative to traditional fire protection methods was investigated [11]. In addition to these fire tests, fire tests on slim floor beams with different web openings were also conducted [12].

In this paper, a finite element modelling (FEM) method is presented to predict the thermal and thermo-mechanical response of slim floors exposed to fire. For this purpose, commercial software, ABAQUS [13] and research software, SAFIR [14], are employed. Both software are used to perform FEM and for computer-aided engineering purposes. In the first part of this study, FE modelling is performed to predict the response of unprotected slim floors in fire. The predicted results are verified against the reported test data. In the later part of this study, the response of intumescent coating applied on a steel member is predicted and verified against the experimental data using a proposed finite element (FE) analysis method. This study is conducted to investigate the response of protected slim floor beams in fire as there is a lack of experimental work. The results from this study will help future researchers to design and plan their experiment work. Finally, the verified models are combined to simulate the behaviour of protected slim floors in fire. Comparative analysis of predictions obtained from both software is performed and the efficiencies and deficiencies associated with each modelling program are highlighted. An earlier study conducted by the authors covers only the thermal behaviour of slim floors in fire [15], however, this research presents a detailed methodology to perform thermal and thermo-mechanical analysis of unprotected and protected slim floor beams. In addition to the performance of each modelling tool, this study also highlights the benefits and deficiencies associated with 2D and 3D FEM approaches and underlines whether the time saving 2D modelling approach is a reliable alternative to a lengthy 3D approach.

2. Previous Experimental Work Used for FEM

The research study presented here is purely based on FEM and analysis while the test data on slim floors and intumescent coatings used during the study are adopted from previous experimental investigations. Details of these experimental investigations are in the following sections.

2.1. Test Data on Slim Floor Assemblies

Various tests were conducted and reported on slim floor assemblies addressing their thermal and structural response in fire (thermo-mechanical). These tests were conducted by different research agencies and industries including Warrington Fire Research Centre (WFRC) and British Steel. The test assemblies used by WFRC and British Steel during their experimental program consisted of rolled asymmetric slim floor beam (ASB) sections and composite slabs. The composite slab of the floor was constructed using deep steel decking and normal weight concrete. Among various others, tests WFRC-66162 and WFRC-67756 were conducted to study the thermal and thermo-mechanical response of asymmetric slim floor beams against standard fire exposure, are used in this study.

Test WFRC 66162 was conducted on 14 February 1996 on a slim floor beam assembly (ASB assembly) 5000 mm long with a 4500 mm span between supports. The tested specimen consisted of an ASB 280 rolled steel beam section and a composite slab constructed using Comflor-210 deep steel decking and normal weight concrete as shown in Figure 1. The nominal depth and width (provided by the manufacturer) of the test assembly were 308 mm and 950 mm, respectively. The steel beam section used was 280 mm deep with top and bottom flanges 180 mm and 280 mm wide, respectively. The nominal distance between the flanges was 244 mm from their inner edges. The thickness of the steel section was 18 mm for the flanges and the web. A layer of concrete, 28 mm deep, reinforced using A-142 steel mesh provided near the finished top surface of the test specimen. Dimensions of the steel section were found to be slightly different from the nominal ones as presented in Table 1.

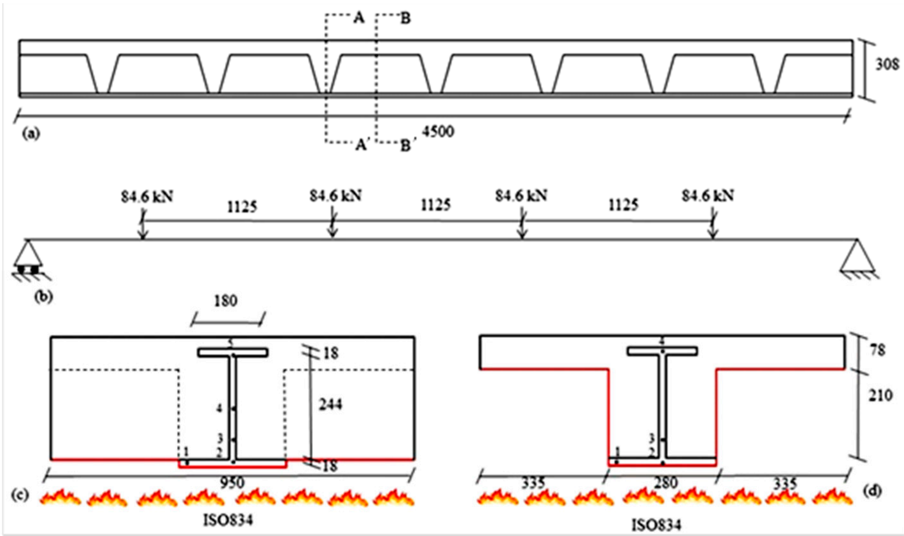


Figure 1. The Tested Specimen WFRC 66162, (**a**) Elevation; (**b**): Loading conditions; (**c**) Section at AA′; (**d**) Section at BB′.

Table 1. Geometric properties of steel sections, WFRC 66162.

S #	Description	WFRC 66162 Provided (mm)	WFRC 66162 Recorded (mm)	WFRC 67756 Provided (mm)	WFRC 67756 Recorded (mm)
1	Depth of ASB	280	279	304	305.8
2	Width of Top Flange	180	183	190	198
3	Width of Bottom Flange	280	280	300	306
4	Average thickness of Top Flange	18	16.6	20	21.7
5	Average thickness of Bottom Flange	18	18.4	20	20.6
6	Thickness of steel Web	18	19.5	18	17.2

Once the dimensions of the ASB were recorded, the tensile strength of structural steel was also investigated which was 402 MPa. This 402 MPa was higher than the tensile strength provided by the manufacturer which was 355 MPa. Further details on this test can be found in a technical note published by British Steel [16].

Comprehensive instrumentation was done to measure temperatures and deformations during the test using 153 K-type thermocouples and linear variable differential transformers (LVDTs) positioned at various locations along the length of the test assembly. These thermocouples were installed at thirteen different locations along the length of the steel section. Additional 30 thermocouples were used to record temperatures in concrete and at 3 locations on the steel decking. Vertical deflections of ASB assembly were measured using LVDTs at six locations along its length including one at the mid-span. External loads were applied at four locations through hydraulic rams positioned 1125 mm apart as shown in Figure 1b. The imposed load of 84.6 kN at each point, in addition to the self–weight of the beam assembly, induced a bending moment of 198.81 kNm which represented a degree of utilisation of 0.423 when compared with the capacity at ambient temperatures of test assembly [16]. Under this load, the test assembly was estimated to achieve a 60 min based on the results from analysis if the enhanced action between steel and concrete was ignored. The test was conducted against ISO-834 standard fire exposure conditions (ISO 834) and the beam assembly was heated for 120 min. The second test, WFRC 67756, was conducted on 4 September 1996 on a slim floor assembly formed using an ASB section and a composite slab [5]. The nominal depth and width of the slim floor assembly were 334 mm and 1000 mm, respectively, Figure 2. The ASB section used was 304 mm deep with a nominal width of the top and bottom flange was 190 mm and 300 mm, respectively. Flanges were 20 mm thick while steel web was 18 mm in thickness. A concrete layer of 30 mm thickness, reinforced with A-142 steel mesh was provided above the top flange. During the test, measured dimensions were found to differ from nominal ones for the steel section as given in Table 1. The measured yield strength of structural steel was 392 MPa, higher than the nominal yield strength of 355 MPa.

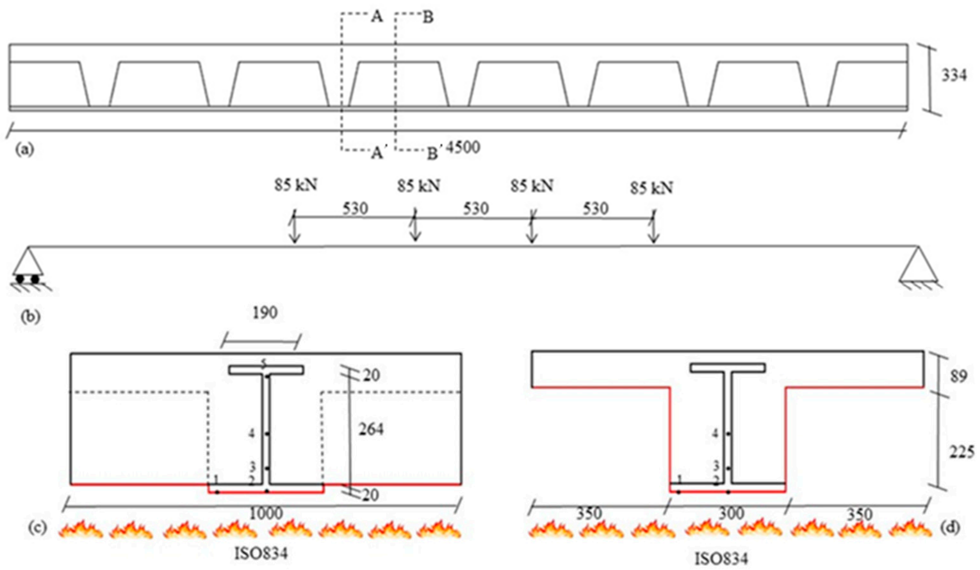


Figure 2. The Tested Specimen WFRC 67756, (**a**) Elevation; (**b**): Loading conditions; (**c**) Section at AA′; (**d**) Section at BB′.

Similar to the previous test, comprehensive instrumentation was done to record temperatures and deflections via thermocouples and LVDTs installed at different positions along the length of the test assembly. Temperatures recordings were taken in concrete and on the steel decking in addition to those on the steel beam section. The external loads, 85 kN each, were applied on the test assembly at four locations through hydraulic rams placed at an intermediate distance of 530 mm as shown in Figure 2b. The applied load and self-weight of the beam assembly induced a bending moment representing the degree of utilisation of 0.390 of its cold capacity. At ambient conditions, the estimated bending moment capacity of the test assembly was 796 kNm, calculated ignoring the enhanced action between steel and concrete. Like in the case of the previous test, the ASB specimen was tested against standard fire exposure conditions and the heating of the beam assembly continued for 90 min.

2.2. Test on Steel Members Protected by Intumescent Coating

The test presented here is a part of an experimental investigation conducted to analyse the behaviour of intumescent coatings for protecting steel members from fire. These experimental investigations were conducted on steel members protected with intumescent coatings. The protected surfaces of the specimens were exposed to standard fire in a gas-fired furnace and the response of intumescent coating at elevated temperatures is analysed, recorded and studied. The test adopted during this part of the research was carried out on steel angle elements protected with an intumescent coating applied on the external surface of one of its legs [17]. The steel angle has legs with external dimensions of 100 mm each in both directions. These legs were 10 mm thick throughout their length. On the external surface of the exposed leg, a 1200 µm intumescent coating layer was applied and the specimen was subjected to fire. The remaining surfaces of the steel member were made adiabatic using mineral wool and plasterboard as shown in Figure 3.

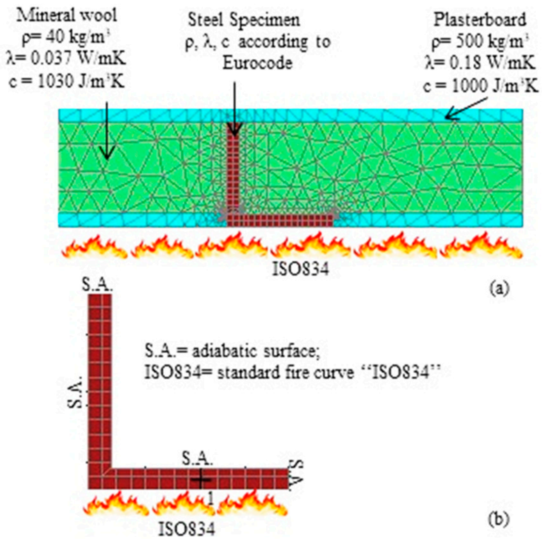


Figure 3. The tested specimen for intumescent coating (**a**) Test assembly, (**b**) The steel member.

The behaviour of intumescent coating in fire depends on different variables, including the section factor [18,19]. The steel member used during the above test has a section factor of 53 m^{-1}. This value of the section factor is very close to the section factors of the slim floor beams used during the tests, WFRC 66162 and WFRC 67756, which have a section factor of 61.5 m^{-1} and 55.08 m^{-1}, respectively. For both slim floor beams, the section factor is determined using Equation (1) [20]. During the analysis, the exterior surfaces of the bottom flange are assumed to be safeguarded against fire. Due to the similar section factor values for the beams and the steel member, it is expected that the fire protection material will exhibit similar behaviour when applied on the slim floor beams as that exhibited during the tests on steel members.

$$\frac{A_{EXP}}{V_{TOT}} = \frac{P_{EXP}}{A_{TOT}} = \frac{P_{EXP\_BOTTOM\_FLANGE}}{A_{EXP\_BOTTOM\_FLANGE}} \tag{1}$$

3. Fine Element Modelling

3.1. The Slim Floors

During this study, FEM is performed for the thermal and thermo-mechanical (structural) response of slim floor systems in 2D is performed using SAFIR while the same in 3D is conducted using ABAQUS. Non-linear temperature thermal related material properties of steel and concrete, the specific heat, density and thermal conductivity, were taken from the Eurocodes [21] (Figure 4). Mechanical properties for steel and concrete were also been taken from the Eurocodes [22,23] (see Figure 4) with the exception that the actual yield strength of steel obtained from the material tests is used instead of its nominal value. Due to changes related to the shape of decking, two sections are selected along the span, section A-A′ with the highest depth and width of concrete around the steel web and section B-B′ with the minimum width and depth of concrete slab (see Figures 1 and 2). During 2D thermal analyses, FE modelling are performed for section A-A′ and section B-B′ separately, while during 3D modelling, full-size models are developed for the test assemblies. External loadings, fire exposure and boundary conditions for both slim floor beams are kept the same during the analysis as those reported for each test. The authors have earlier conducted a study on the thermal response of slim floor systems using FEM. In these studies, it was found that the predicted results for 2D modelling using both software, ABAQUS and SAFIR, were similar. Hence, during this study, FEM in 2D will only be performed using SAFIR. During the 2D modelling, 43-node linear quadrilateral heat transfer elements are employed, while for 3D modelling, 8 node hexahedral solid linear heat transfer elements, DC3D8 are used to perform the thermal analysis. Following the recommendations of the Eurocodes [18], convection coefficients for unexposed and exposed edges/surfaces are taken as 9 W/m^{2}K and 25 W/m^{2}K, respectively. Radiation emissivity for the exposed steel and concrete edges/surfaces is taken 0.5 and 0.25, respectively, as reported previously [24]. During the thermal analysis, any heat losses resulting from radiation from the unexposed edges/surfaces have been ignored. The temperature predictions obtained during this part of the analysis are later applied to ASBs to examine the influence of fire on their structural response. During the second part, structural analyses were conducted in two steps. In the first step, external loads were applied on the slim floor beam assembly, while in the second step, the beam assembly was exposed to temperature predictions obtained during the first part, the thermal analysis. The non-linear behaviour of concrete was modelled using ‘the concrete damaged plasticity model’ while the same for steel has been modelled using ‘Von Mises plastic model’. The dilation angle for concrete was set to 55° as suggested previously by researchers [24].

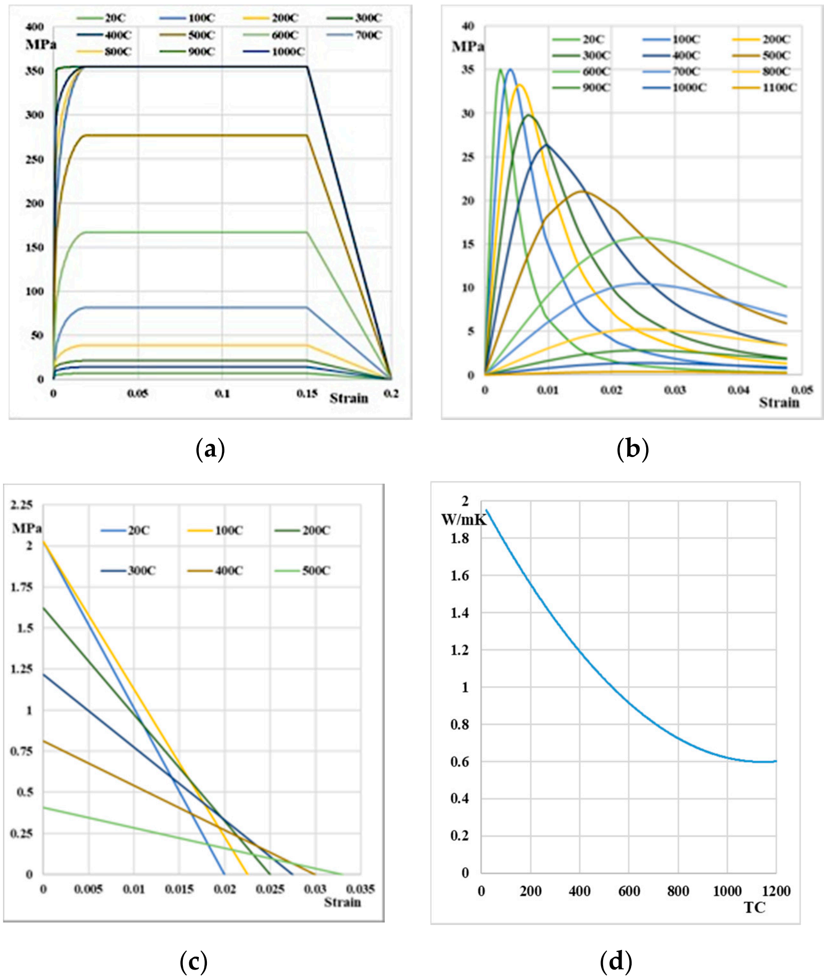


Figure 4. Temperature-dependent properties, (**a**) Stress-strain curve of structural steel, (**b**) compressive behaviour concrete, (**c**) Tensile Behaviour Concrete, (**d**) Thermal conductivity of concrete.

A uniformly distributed load representing the test loads was applied during FEM. Structural FE analysis in 2D using SAFIR was performed using 43–node beam elements and section A-A′ and section B–B′ was were assigned to the specimen at respective locations along its span. In particular, the 2D beam's mechanical model consists of an alternation of sections section A-A′ and section B-B′, to simulate the presence of different cross-sections also in the 2D model (see Figure 1). The structural analysis in 3D with ABAQUS was performed using different analysis elements for concrete and steel. The concrete part was modelled using 8-node linear brick elements, C3D8, while the steel part was modelled with incompatible mode elements, C3D8I as these elements were found to be more suitable in comparison with other available element types in ABAQUS [13]. In the case of SAFIR, perfect thermal and mechanical contact is modelled by default and no option is available to include frictional and thermal losses between the steel and concrete. While in ABAQUS, contact between concrete and steel can be modelled using the contact pair facility of ABAQUS. During thermal analysis, perfect thermal contact is modelled at the interface of the two materials which does not allow any heat losses. On the other hand, during the structural analysis, tangential behaviour and interaction between concrete and steel were modelled using the 'Coulomb friction model' by defining a coefficient of friction of 0.5 [25].

3.2. Test on Steel Member Protected with Intumescent Coating

The test on steel members protected with an intumescent coating is modelled in 2D using SAFIR, where 4-node linear quadrilateral heat transfer elements are used. The initial thickness of the intumescent coating, constant with time was modelled and the perfect thermal contact between steel and intumescent coating is considered during the analysis. The same in 3D is modelled using ABAQUS, were similar to the slim floor case, 8 node hexahedral solid linear heat transfer elements, DC3D8, employed to study its thermal response. Thermal properties of the structural steel including the thermal conductivity and specific heat, in both cases, are adopted from the Eurocodes [26].

Material properties of the intumescent coating, specific heat, density, water content, convection coefficient and radiation emissivity are used from an earlier research study performed previously [27]. For the unprotected exposed edges/surfaces, convection coefficient and radiation emissivity are 20 and 0.95, respectively [27], Table 2.

Table 2. Thermal properties of intumescent coating (IC) [21].

Specific Heat [J/kgK)]	**1200**
Density of IC [kg/m^3]	200
Water content of IC	0
Exposed Surfaces, Convection coefficient for IC	20
Radiation emissivity value for IC surface	0.95

Temperatures dependent thermal conductivity of the applied intumescent coating was taken from the data acquired during the previous test discussed in Section 2.2 [17]. The thermal conductivity with respect to time is presented in Table 3.

Table 3. Thermal conductivity of Intumescent Coating [17].

T (°C)	**20**	**182**	**377**	**423**	**610**	**644**	**651**	**759**	**835**	**871**	**881**	**892**	**1200**
λp (W/mK)	53.3	0.02	0.02	0.02	0.02	0.03	0.04	0.03	0.01	0.008	0.009	0.026	0.026

The FE analysis for the intumescent coating test is performed to verify the results from FEM against the test data so that the verified FEM method can be used to analyse the response of intumescent coating used as a fire protection material applied on the protected slim floor beams. As the fire protection materials do not have any contribution towards the structural resistance of members, hence, FEM for the intumescent coating material is kept limited to thermal response only.

3.3. Protected Slim Floor Beam Assemblies

The FE analysis for the protected slim floor beams was performed by combining the verified FEM models for unprotected slim floor tests and the test on steel members with the intumescent coating described above. The protected slim floors are the same as the unprotected ones described previously but a layer of intumescent coating, a layer with 1200 μm thickness, is applied on the exposed edges/surfaces of the bottom flange of the steel beam section as shown in Figure 5. In the case of 2D modelling, edges of the steel part are protected while in the case of 3D modelling, exposed surfaces of the bottom flange are protected. The thermal and mechanical properties of all materials are the same as those discussed previously. Response of protected slim floors in fire was conducted in two phases, thermal and structural. In the first phase, temperature predictions are obtained for the protected slim floors and temperature predictions were obtained, while in the second phase, the structural response was studied under the effect of loading and heating in two steps. Firstly, loads are applied and then the floors were heated using the thermal predictions obtained during the first phase. This FE investigation was conducted to analyse the response of protected slim floors in fire. During this investigation, the protected slim floor beams were exposed to the same external loads as used during the tests conducted on unprotected slim floor beams. As mentioned before, any contribution of the intumescent coating towards the strength and stiffness of the slim floor assemblies was ignored.

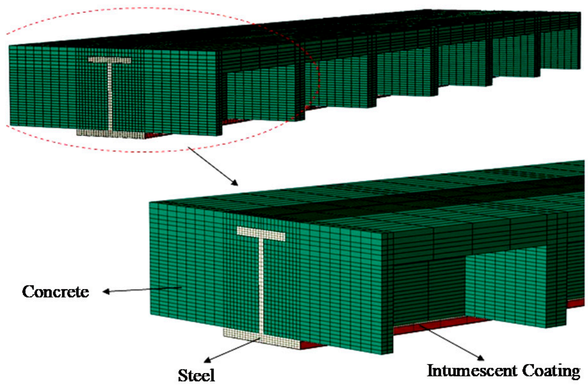


Figure 5. Slim floor protected with an intumescent coating.

4. Results and Observations

In this section, predictions on the thermal and structural response of slim floor beams obtained from FEM are presented against the test data for unprotected slim floors and the intumescent coating test. For protected beams, the predicted thermal and structural response is presented in comparison with that of the unprotected slim floor beam specimens to highlight the effects of fire protection materials on their behaviour.

4.1. Unprotected Slim Floor Specimens

During the fire tests, WFRC 66162 and WFRC 67756, data recordings were conducted in terms of temperatures and vertical deformations. The recorded data has been reported in form of MS excel files and is available on the website, steelconstructin.info [28]. Though thermal data was recorded at various locations, comparisons are made only for two selected locations for each slim floor specimen to avoid any repetitions. These locations represent the middle part of the test assembly which is almost free from any influences resulting from the presence of boundaries such as the furnace walls. Further, the structural response of both slim floor beams was analysed via mid-span deflection in comparison to that recorded during the tests.

Thermal results from FEM are presented for selected thermocouple positions at sections A-A′ and section B-B′ for test WFRC 66162 in Figure 6. The thermal gradient across the section after 120 min of heating is significant at both locations as seen in Figure 6a,b.

Thermal predictions obtained using SAFIR and ABAQUS are presented in comparison to the recorded test data, Figure 6c,d. It is seen that the thermal predictions are in good agreement for 3D analysis irrespective of the position of the thermocouples across the section. On the other hand, these predictions slightly differ for thermocouples locations 3, 4 and 5 located on the web for 2D FEM performed using SAFIR as shown in Figure 5. This is due to the limitations of 2D modelling where the boundary conditions along the span cannot be modelled due to limitations of the approach. During the tests, heat also transfers toward section A-A′ from the thin exposed sides of the concrete ribs due to the steel decking shape. This heat is in addition to the heat coming from the exposed bottom parts of the flange. The heat transfer from the ribs of the concrete cannot be modelled using the 2D FEM approach as result lower temperatures are predicted on the web. Hence, the predicted temperatures using 2D FEM for this part are lesser than those recorded during the test. On the other hand, thermal predictions result from 2D and 3D FEM for section B-B′ are in good agreement with the recorded test data for section B-B′ as boundary conditions were modelled with accuracy for both modelling methods (Figure 6d). In this case, the temperature provided by the 2D model are generally greater than those obtained applying the 3D model, as no longitudinal heat flux is considered in the 2D model.

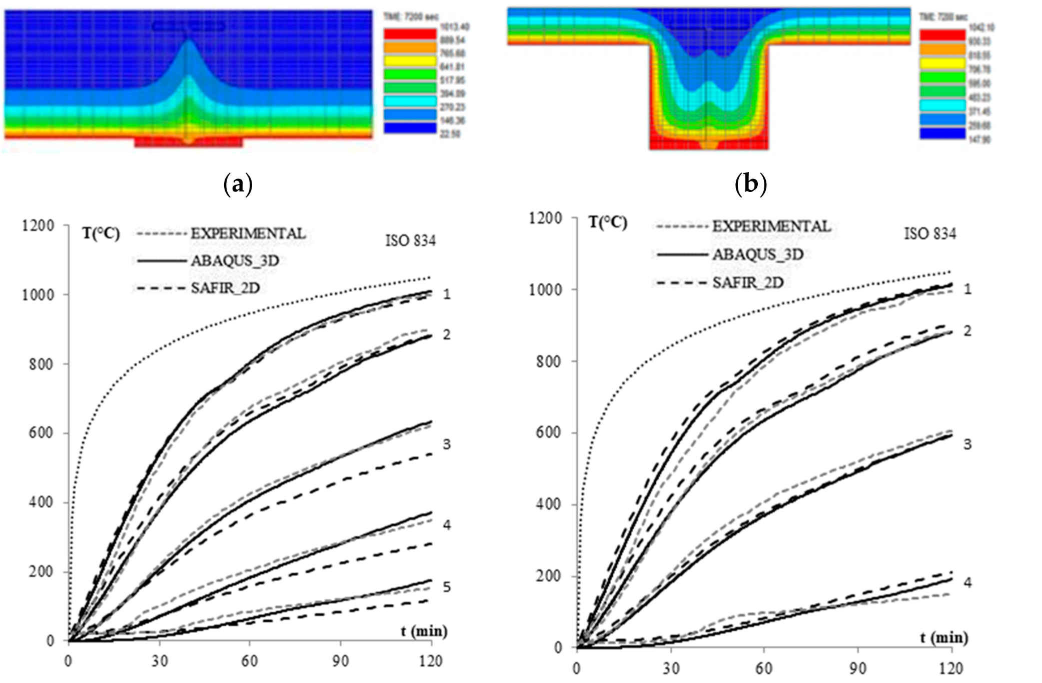


Figure 6. Thermal comparisons for WFRC 66162: (**a**) Thermal contours at section AA′ after 120 min, (**b**) Thermal contours at section BB′ after 120 min, (**c**) Test vs. FEM at section AA′ (**d**) Test vs. FEM at section BB′.

The thermal analysis method used is further assessed by analysing the predictions obtained on the thermal behaviour for WFRC 67756 with respect to the recorded test data. Like the previous case, data comparisons have been made for section A-A′ and section B-B′ and are presented in Figure 6. The 3D FEM results are in very good agreement with the test data for both locations. The obtained FE results from 2D modelling are in good agreement for section B-B′ while in the case of thermocouples located on the steel web, the results differ slightly from the test data for section A–A′, Figure 7c,d. It should be kept in mind that the thermal results estimated from 2D and 3D modelling are in good agreement with the test data, however, 3D modelling yields better results in comparison to 2D modelling. This indicates that the FEM approach in 2D and 3D adopted for thermal analysis of slim floors can be used for the fire design and verification of these systems with high confidence to predict their thermal behaviour in fire, with the great benefit of reducing the computational burden.

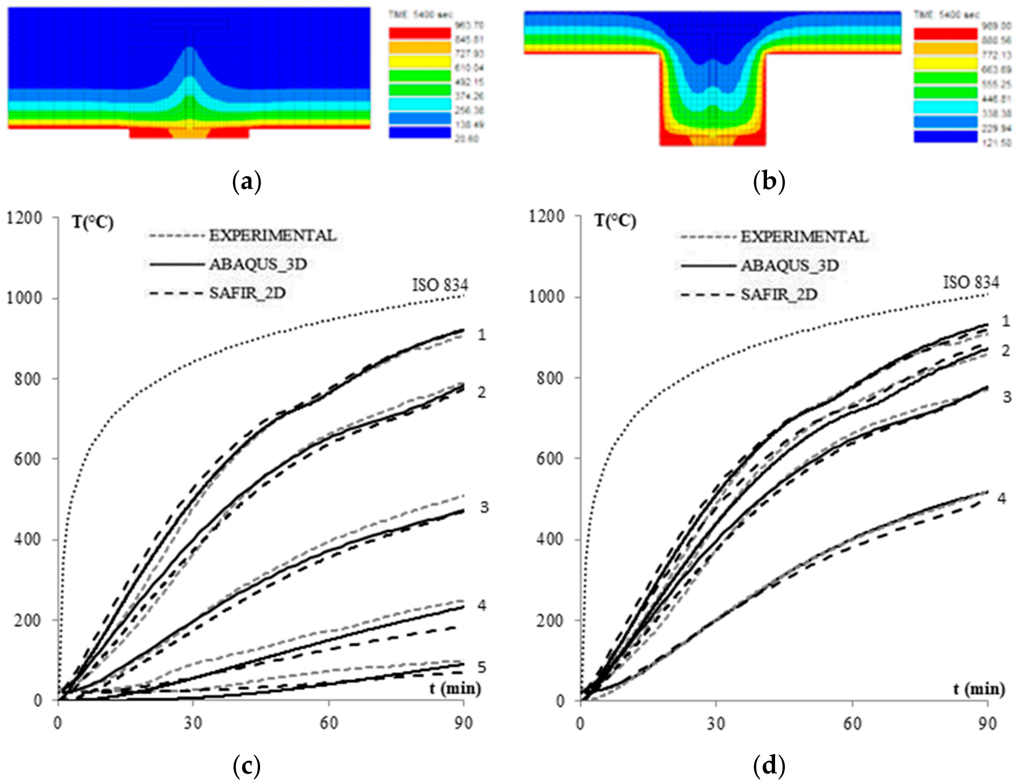


Figure 7. Thermal comparisons for WFRC 67756: (**a**) Thermal contours at section AA′ after 90 min, (**b**) Thermal contours at section BB′ after 90 min, (**c**) Test vs. FEM at section AA′ (**d**) Test vs. FEM at section BB′.

The structural response of ASBs in fire was estimated through their mid-span deflection. Figure 8 shows the predicted and measured mid-span deflection for tests WFRC 66162 and WFRC 67756. The predicted deflections are in good agreement with the test data for both beam assemblies. The mid-span deflections predicted using 3D modelling (using ABAQUS) are better as compared to those obtained from 2D modelling using SAFIR, however, both approaches yield good results.

Hence the proposed FEM approach is not only capable of predicting the thermal behaviour, but it also predicts the structural response of slim floor beams with considerable accuracy. These results also show that the simplified 2D FE approach provides conservative results for structural response in terms of mid-span deflections. This may probably result due to more severe thermal field evaluated for the section B-B′, which is the widely distributed section along the span of the slim floor beam assemblies resulting from the shape of steel decking.

The good agreement of 2D models not only in terms of temperatures but also in terms of displacements both with 3D model and experimental results further emphasises the possibility of using a simple 2D model in the design and verification of the slim floor beams, according to the technical fire regulation.

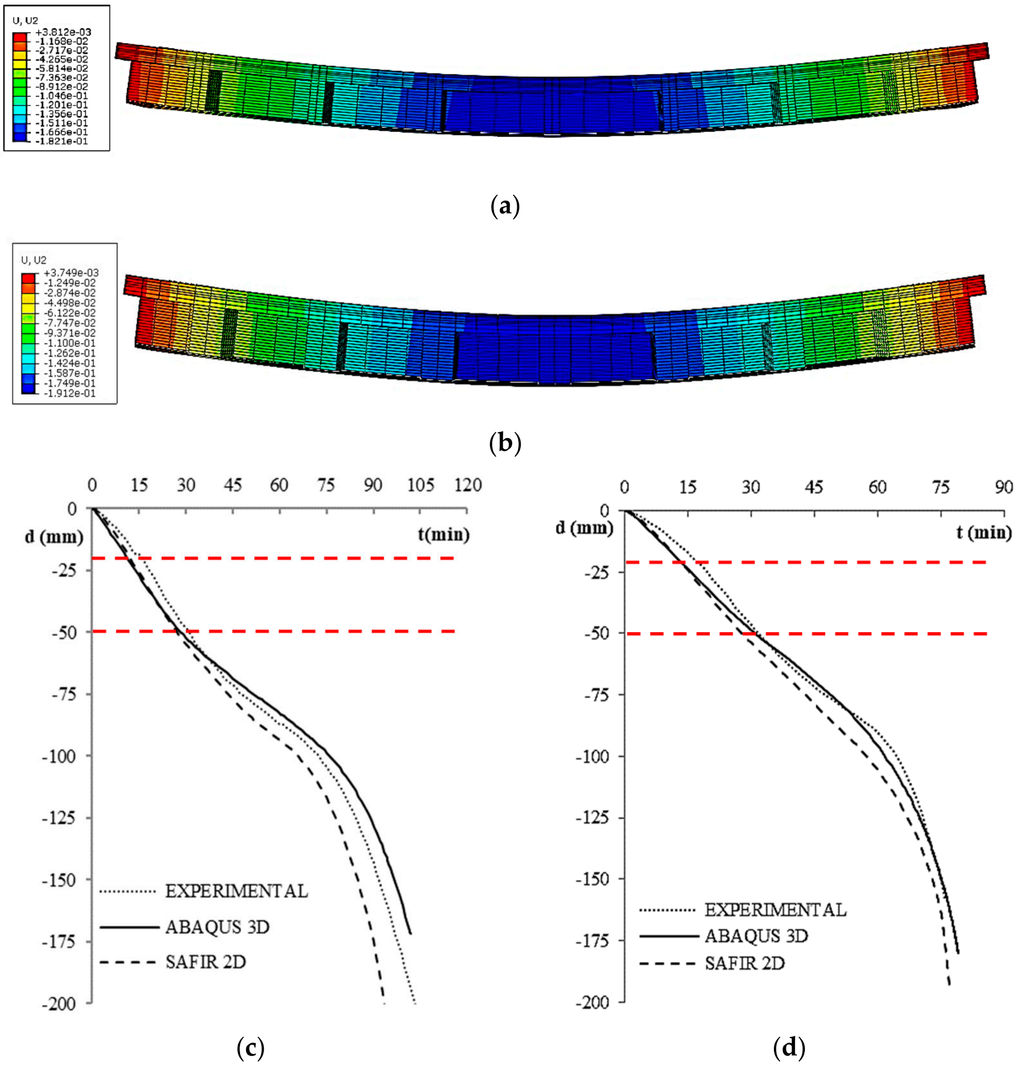


Figure 8. Experimental vs. predicted mid-spand deflections for 2D and 3D FEM: (**a**) Deflected shape of WFRC 66162 after 102 min, (**b**) Deflected shape of WFRC 67756 after 79 min, (**c**) Mid-span deflection, Test vs. FEM for WFRC 66162, (**d**) Mid-span deflection, Test vs. FEM for WFRC 67756.

For example, the European codes [25] define five safety performance levels for the building fire resistance design, depending on the building intended use and its importance [29]:

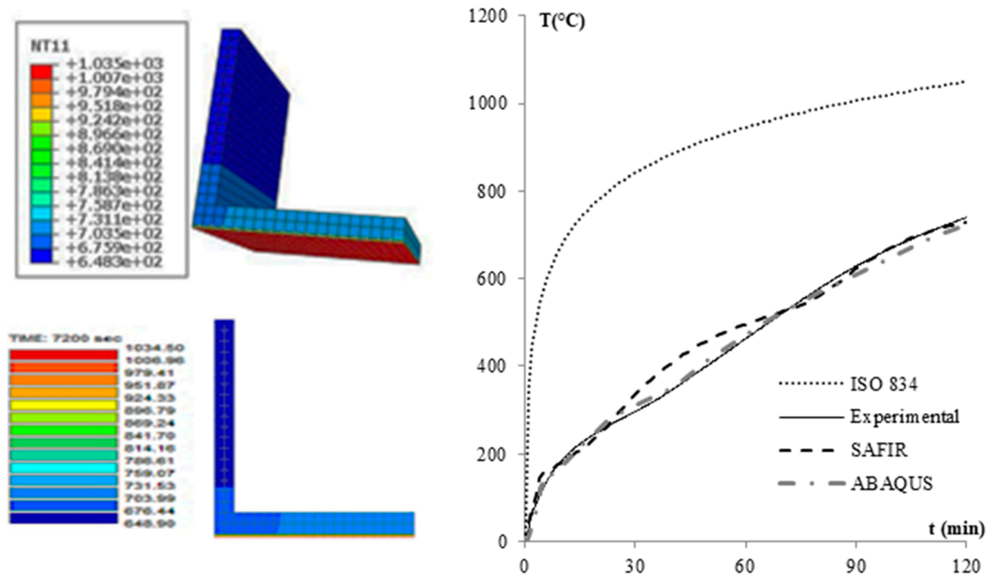
- Level I: no external consequences for structural collapse;
- Level II: maintaining the fire resistance requirements for a period of time sufficient for the evacuation of occupants.
- Level III: maintaining the fire resistance requirements for the natural fire duration;
- Level IV: limited damage of the structure after fire exposure;
- Level V: complete serviceability of the structure after fire exposure.

Focusing on Level IV or Level V, which in many cases are requested to the structures, the Italian Code for Fire Safety fix the displacement capacity corresponding to the achievement of the value of 1/100 and 1/250 of the length of the structural components, respectively. Applying these limit values (50 mm and 20 mm) to the analysed beams, both the performance levels are not satisfied and designing a protection material that can reduce the temperatures in the structural sections and improve the fire response of the beam, is necessary. In the following, the results of the simulation of the slim floor protected with intumescent coating are shown, modelling this reactive material according to the method described before and in [17].

4.2. The Fire Protection Material-Intumescent Coating

Response of the intumescent coating material at elevated temperatures is analysed in terms of temperature development in the steel member on which it is applied. The position of the thermocouple selected during the FEM is similar to the ones used to record the temperature of the steel member during the furnace test and is shown in Figure 3.

Thermal contours obtained from FEM at the end of 120 min using ABAQUS and SAFIR are presented in Figure 9a. It can be seen in Figure 9a that a momentous temperature difference is predicted for the exposed surface of the intumescent coating and that of the adjacent steel part on which it is applied. This temperature difference is the result of the lower thermal conductivity of intumescent coating which at higher temperatures expands, protecting steel from reaching high temperatures.



(**a**) (**b**)

Figure 9. Test data and analytical results for Intumescent Coating test: (**a**) Results at the end of 120 min of analytical modelling, (**b**) Comparison of analytical results and the test data.

Thermal predictions obtained from 2D and 3D FE modelling using SAFIR and ABAQUS at the thermocouple location are presented in comparison with the recorded test data in Figure 9b. It is seen that FEM results for both cases are in close agreement with the test data, hence, the FEM approach yields reliable results. In other words, the proposed FE modelling method provides good predictions for the thermal response of the intumescent coatings at elevated temperatures when applied as a fire protection material on steel members.

4.3. Slim Floor Systems Protected with Intumescent Coating

FEM for the slim floor beams assumed to be protected by a layer of intumescent coating on the exposed edges/surfaces of the lower flange is conducted by combining the verified models for unprotected slim floor beams and steel members with intumescent coating. The thermal estimates obtained from numerical modelling for the protected slim floors are plotted against the test data for unprotected tests WFRC 66162 and WFRC 67756 in Figures 10 and 11, respectively.

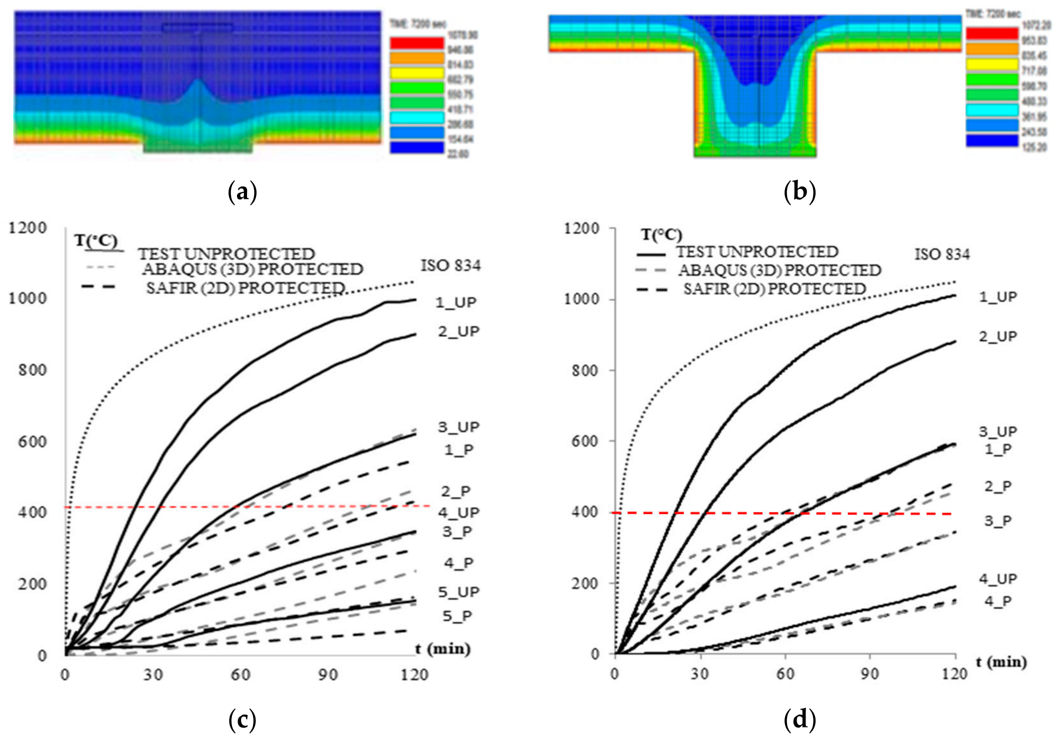


Figure 10. Effectiveness of IC in terms of temperatures predictions for protected vs. recorded for unprotected, WFRC 66162: (**a**) Thermal contours for the protected beam at section AA′ after 120 min, (**b**) Thermal contours for the protected beam at section BB′ after 120 min, (**c**) Protected vs. Unprotected at section AA′ (**d**) Protected vs. Unprotected at section BB′.

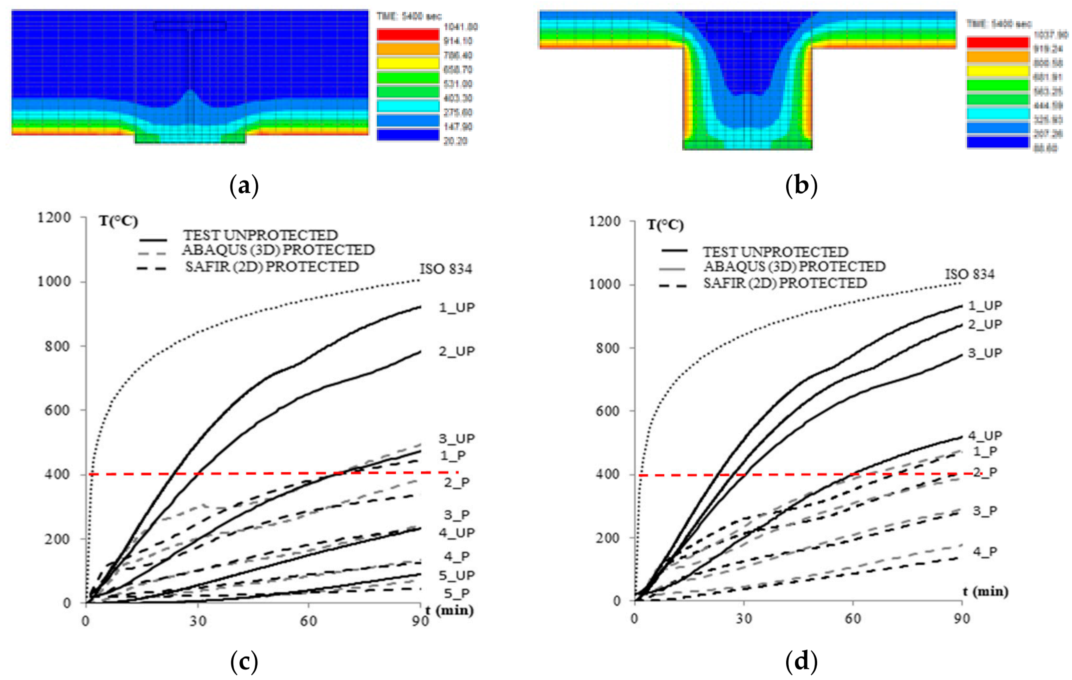


Figure 11. Effectiveness of IC in terms of temperatures predictions for protected vs. recorded for unprotected, WFRC 67756: (**a**) Thermal contours for the protected beam at section AA′ after 90 min, (**b**) Thermal contours for the protected beam at section BB′ after 90 min, (**c**) Protected vs. Unprotected at section AA′ (**d**) Protected vs. Unprotected at section BB′.

As expected, it is found that the applied intumescent coating (1200 µm) significantly restricts the temperature developments on the steel section when compared to those recorded for the unprotected ASBs. The parts of the steel beam section which are closer to exposed surface/edges, the temperature reduction in temperature is more significant. This difference reduces with the increase in the distance towards the unexposed upper surfaces/edges. The steel parts away from the protection layer are less influenced by its application of intumescent coating as they are already encased in the concrete slab which protects them from direct exposure to fire by providing adequate insulation. In both cases, the temperatures recorded on the steel section are below 400 °C even after a fire exposure of more than 60 min, hence, the specimens retain their full strength/capacity and stiffness for this duration of fire exposure. Further, the structural response has improved significantly for both SFB assemblies.

Figures 12 and 13 show that both protected slim floor beams offered an enhanced fire resistance against the standard fire curve. Both slim floor beams continued to support the external loads for more than 120 min. At 120 min, the FE analysis was discontinued and the mid-span deflection for both beams was predicted to be less than 60 mm for both FEM approaches, 2D and 3D. Hence, the slim floors protected using a 1200 µm thick layer of the intumescent coating can offer fire resistance of more than 120 min for the same utilisation factors as those used during the tests. Moreover, the slim floor beams protected with 1200 µm can satisfy the performance levels IV with limited damage of the structure after fire exposure; indeed, the maximum displacement is less than 50 mm for 120 min. For satisfying the performance level V, a greater thickness of protection is necessary for reaching 120 min; indeed, Figures 12 and 13 show that the maximum displacement is lower than the limit one for a time of 30 min.

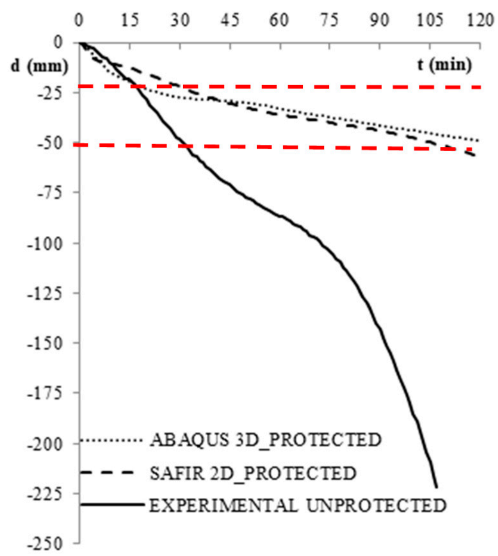


Figure 12. Effectiveness of Intumescent Coating: predicted deflection for protected slim floor vs. recorded deflection for the unprotected slim floor, WFRC 66162.

It should be noted that the protected specimen continued to support the loads beyond 120 min, however, the FE analysis was discontinued at this point.

The structural response of protected slim floor beams is analysed using the same approach as that used for the unprotected slim floors where loads are applied in the first step on the upper flange of the steel section and in the second step, the specimen is heated using the temperature predictions obtained from the thermal analysis. Loading conditions are kept the same as those used during the experimental programme with a degree of utilisation 0.423 and 0.369 for WFRC 66162 and WFRC 67756, respectively.

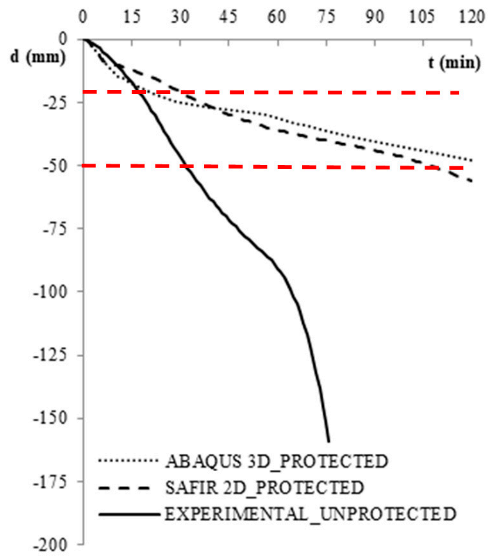


Figure 13. Effectiveness of Intumescent Coating: predicted deflection for protected slim floor vs. recorded deflection for the unprotected slim floor, WFRC 67756.

5. Conclusions and Future Work/Recommendations

This research presents a finite element modelling method to investigate the thermal and structural response of unprotected and protected slim floors using commercial software (ABAQUS) and research software (SAFIR). The modelling software are employed to perform FE analysis in 2D and 3D and the thermal and structural response is replicated and verified against the recorded test data for two unprotected slim floor beam assemblies. Thermal predictions for a test on a steel member protected with the intumescent coating is later simulated and verified against the test data. The verified models are finally combined to simulate and predict the thermal and structural response of slim floor beams protected with an intumescent coating. Fire performance of slim floors, protected and unprotected are not covered by the current design codes, hence, this study may help to contribute to devising simple fire design methods for these beam types in future. Conclusions from this study and the potential future developments are listed below:

- although the time requirements for 3D finite element modelling are significantly higher than those require for 2D modelling, both 2D and 3D finite element modelling approaches give good predictions for thermal behaviour and structural response of slim floor beams in fire. This suggests that 2D modelling is a time-saving alternative to 3D modelling of slim floor beams in fire without largely compromising on the results;
- although 2D modelling yields good reliable results, the 3D modelling method gives better predictions for the thermal and structural response of slim floors as it can accommodate the geometric variations resulting from the shape of steel decking along the length of the slim floor beams. In the case of the steel decking with more variations along the length, the accuracy of 2D modelling may be compromised;
- during the model validation process it was observed that both 2D and 3D FEM analysis predict the thermal response of intumescent coating with good agreement with the test data;
- in the case of protected slim floors, temperatures in the steel section are significantly reduced due to the presence of the intumescent coatings, resulting in better fire resistance. These observations were equally valid for both 2D and 3D modelling;
- thermal predictions obtained using 2D and 3D modelling for protected slim floors show that temperatures in the steel section remain within 400 °C for 60 min of standard fire exposure. This means that the strength of the steel section will largely remain available to resist the applied loads;

- protected slim floors used in this study offered a fire resistance of more than 120 min under degrees of utilisation of 0.423 and 0.3690;
- using 1200 μm of intumescent coating thickness, the performance level IV can be satisfied for 120 min;
- for satisfying the displacement limit of the performance level V for 120 min, a greater thickness of the intumescent coating is necessary, because with 1200 μm the limit is respected for 30 min.

The current study on protected slim floors is limited to finite element modelling only, hence, future developments include experimental tests on protected slim floors to study their response in fire and to validate the results of the finite element modelling approach presented in this work. Further, more studies using FEM should be conducted to analyse the influence of the protection thickness on the response of slim floor beams in fire.

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